**Title:** The ODD+D protocol for the Multilevel Group Selection I (MGS I) model

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This document follows the ODD (Grimm et al., 2006, 2010) protocol.

# 1. Overview

This section provides an overview of the Multilevel Group Selection I (MGS I) model.

## 1.1 Purpose

The MGS I model simulates a population of contributing and non-contributing agents, competing on a social landscape for higher-value spots in an effort to withstand some selection pressure. It may be useful to both scientists and students in hypothesis testing, theory development, or more generally in understanding multilevel group selection.

## 1.2 Entities, state variables and scales

During setup, contributing and not-contributing agents randomly distribute throughout a social landscape. Groups emerge on the landscape when agents self-organize into adjacent spots, with the dynamic size of each group depending on the number of occupied adjacent spots. The landscape size and agent density determine the size of the agent population, while the initial percentage of contributing agents determines its composition. Contributing agents (orange) are those that currently contribute all of their resources to their group, but that may choose to stop doing so under a change in conditions. Not-contributing agents (blue) are those that currently do not contribute any of their resources to their group, but may choose to start.

## 1.3 Process overview and scheduling

Each period begins with the agents acquiring the same amount of resource units. Additionally, the strength of the selection pressure (measured in resource units) increases by an increment. During a period, agents take turns analyzing the value of unoccupied spots and move to the one with the highest expected value (in resource units), as long as its value is greater than that of their current spot. The spot values in each agent's analysis at this point are only expected, as opposed to actual, since both the size and composition of the group may change after the agent moves and before it can benefit from the group. The following equation (Eq. 1) represents the dynamic expected value of each spot i ($1 \leq i \leq N$):

$$s_i = m * (\sum_{j=1}^{N_i} r_j) \; / \; N_i \qquad \text{Eq. 1}$$

where $r_j$ is the number of resource units the agent considering spot $i$ expects current group member in spot $j$ to contribute to the group. $\sum_{j=1}^{N_i} r_j$ is the total number of resource units the agent considering spot $i$ expects all members (including itself) to contribute to their group. $N_i$ ($1 \leq N_i \leq 9$) is the current number of agents in the group, including the agent in spot i. Lastly, m is the multiplier effect from group members contributing their resources.[1]

When m is at 1, it has no effect on the overall value of contributions into a group. When greater than 1, it increases the overall value of contributions, making a group member's contribution a benefit to their group. When less than 1, it reduces the value of overall contributions, making a contribution a cost to their group. It is worth noting that the number of non-contributors in the group is both linearly and negatively correlated with the benefit/cost of contributions.

After all agents had the chance to move, agents either contribute their resources to their group or do not, depending on their type, with the following equation (Eq. 2) representing each agent's resulting amount of resource units:

$$rr_i = r - r_i + m * (\sum_{j=1}^{N_i} sr_j) \; / \; N_i \qquad \text{Eq. 2}$$

where r is the number of resource units the agent acquired at the beginning of the period. $r_i = [0, r]$ is the number of resource units agent $i$ contributed to its group during the period. $\sum_{j=1}^{N_i} r_j$ is the total number of resource units contributed to the group by all group members (including agent

[1] This formulation creates significant overlap between agent groups, i.e., agents are simultaneously benefitting from the contributions made in numerous groups. This overlap adds an unnecessary level of complexity. To simplify things, agents only engage in their own group's common-pool, the one including their direct neighbors and themselves. While the simplification may change outcome values, it does not change the fundamentals and sufficiently allows for multilevel group selection.

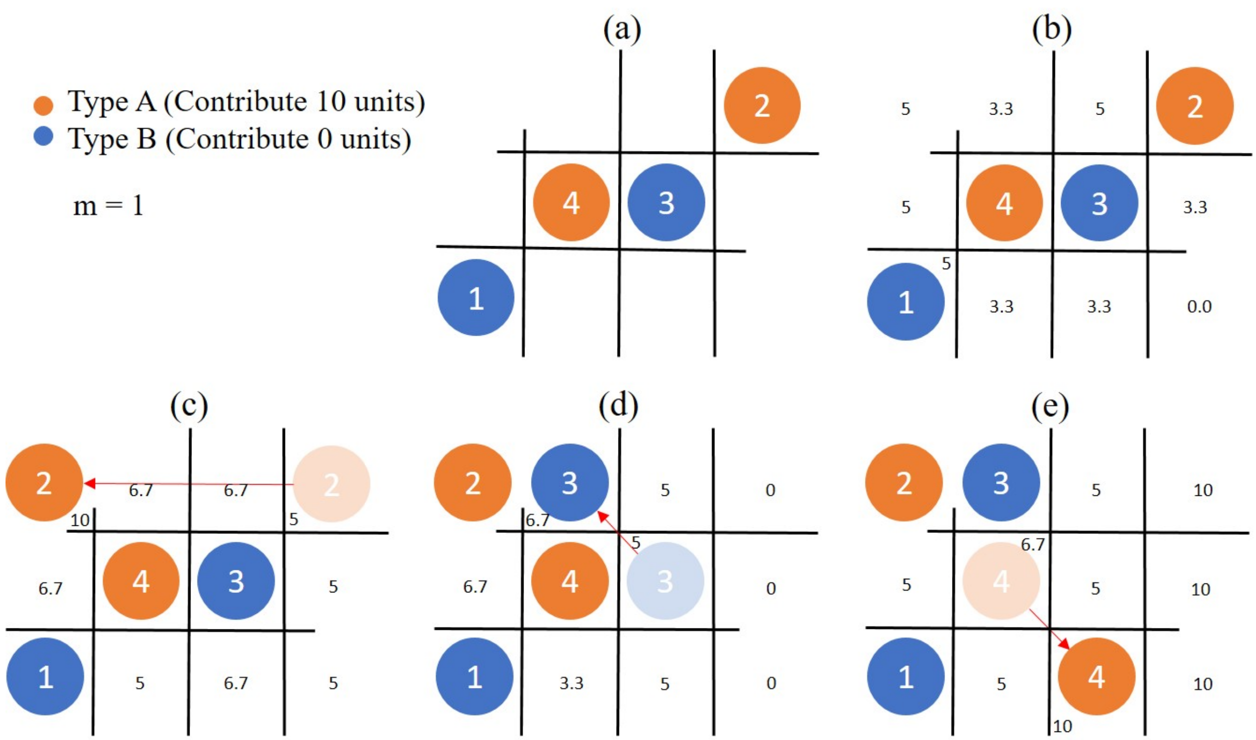
i) during the period. $(\sum_{j=1}^{N_i} r_j) \ / \ N_i$ is the average number of resource units contributed by all group members during the period. m is the multiplier effect from group members contributing their resources during the period. m/N is the multiplier effect per capita from group members contributing their resources during the period. Lastly, $m * (\sum_{j=1}^{N_i} r_j) \ / \ N_i$ is the number of resource units gained by agent $i$ from their group during the period.

After each agent calculates its resulting amount of resource units, it compares the total to the current strength level of the selection pressure. If the strength level is equal to or exceeds the agent's resulting amount of resource units, the agent reconsiders and potentially changes its position on contributing. The likelihood of their continuing or starting to contribute is both linearly and positively correlated with the current percent of contributing agents in the population. A period ends after all agents had a chance to reconsider and possibly change their willingness to contribute, at which point the current percent of contributing agents in the population updates accordingly. If, as a result, the current percent of contributing agents equals 0 or 100, the model stops simulating. Otherwise, the next period starts, following the same sequence of steps as described above.

Figure 1 provides an example of how agents use spot values to decide where to move. For simplicity of calculations, let us assume that the multiplier effect from contributing is 1 (i.e., there is no benefit to the group from members contributing). Figure 1a depicts the initial distribution of agents. Figure 1b depicts the expected value of available social spots from Agent 1's perspective, as it decides where to move. The value of each spot is based on how much Agent 1 expects to receive from a group if it moves to or remains at a spot. The calculations are specific to Agent 1's perspective, as its type (in cases when the multiplier effect is not set to 1) may influence how much it would receive from the group.

For example, if Agent 1 were to remain at its current spot, it would expect to receive five resource units from its group. The number is calculated as follows (Eq. 2): 1 * (0 + 10) / 2 = 5. Since five is the highest expected value of a spot, Agent 1 will decide to remain at its current spot. However, the actual amount Agent 1 receives from the spot's group depends on whether/how the composition of its group is influenced by movements of other agents scheduled to move after Agent 1. In other words, there may be a difference between the expected and actual amounts received. This is because an agent sets its expectations right before it moves, while how much it actually receives is calculated after all the agents had a chance to move.

**Figure 1:** An example of how agents in the MGS I model use spot values to decide where to move.




Figures 1c, 1d, and 1e make the same calculations from the perspectives of agents 2, 3, and 4, respectively, when it is their turn to move. Based on the depicted movements of Agents 2, 3, and 4, Agent 1 will end up receiving zero from the group (Fig. 1e).

## 2. Design concepts

### 2.1 Theoretical and empirical background

The MGS I model has three main theoretical influences that shaped its design. The first is multilevel (group) selection theory (Boyd, 2018; Goodnight & Stevens, 1997; Sober & Wilson, 1999; Waring et al., 2015; Wilson & Sober, 1994; Wilson & Wilson, 2007). The theory explains how a group's composition and *within*-group interaction can influence its competitiveness against that of other groups and as a result allow for selection to occur at both the level of the individual and the group. The MGS I model's design followed Sober and Wilson's (1999) set of criteria for the emergence of multilevel selection, which requires: (a) the presence of more than one group, (b) group heterogeneity (in respect to the trait), (c) a direct and positive relationship between the number of members carrying the trait and the fitness of a group, and (d) isolation among sets of agents significant enough to form groups but not so significant as to prevent between-group migration.

Another major influence is Schelling's (1971, 1978) research into segregation, which demonstrates how even a minor bias influencing residents' relocation preference can lead to an unexpected outcome, such as segregation of the entire population. In Schelling's agent-based model, each agent's preference influences the value of adjacent spots for other agents. As each agent moves in search of better spots, they potentially influence the values of their old and new adjacent spots. Agents moving from one neighborhood to another represents a dynamic neighborhood selection process, with *within*-neighborhood dynamics driving *between*-neighborhood dynamics and the two being closely intertwined. The MGS I model reinterprets Schelling's neighborhoods as common-pools (Ostrom et al., 1994), with the movement of agents representing a dynamic common-pool selection process within a landscape of social spots. Schelling's model helped fulfill Sober and Wilson's criteria a, b, and d.

The last main influence are common-pool games (Chaudhuri, 2011; Holt & Laury, 2002; Ledyard, 1994; Levitt & List, 2007; McGinty & Milam, 2013), from which the MGS I model borrows the equations for calculating the expected and actual spot values, as well as the benefits gained by agents from participating in common pools. The equations from common-pool games helped satisfy Sober and Wilson's criterion c.

## 2.2 Individual decision-making

Agents make two decisions. One relates to where to move. Agents consider all unoccupied spots and move to the one with the highest value. The other decision relates to whether to change their position on the practice.

## 2.3 Learning

Agents do not learn.

## 2.4 Individual sensing

Agents sense the precise current percentage of contributing agents in their population. They also sense the precise number of contributing and non-contributing agents in the unoccupied spots and can calculate their expected contribution.

## 2.5 Individual prediction

When deciding where to move, agents identify with precision the most valuable spot out of the unoccupied spots. However, if they are not the last agent to move, movement by other agents may increase or reduce the value of the spot. This property stems from Schelling's (1971, 1978) segregation model, in which with every move an agent not only changes their own neighborhood composition, but also for their old and new neighbors.

## 2.6 Interaction

Agents interact indirectly by either contributing or not into a group.

## 2.7 Collectives

Groups of size 2 to 9 emerge whenever two or more agents move (self-organize) into adjacent spots.

## 2.8 Heterogeneity

Agents differ based on their location and position on the collective practice, which means they either contribute or not. Spots differ based on location, their state of occupancy, their actual value to their agent, and their expected value to contributing and non-contributing agents.

## 2.9 Stochasticity

The following processes use a uniform random distribution:

- Initial distribution of agents.
- Initial state (contributing vs. non-contributing) of distributed agents.
- The sequence in which agents consider moving and possibly move.
- The likelihood an agent switches positions. This process is based on the current percentage of contributing agents in the population.

## 2.10 Observation

The current percentage of contributing agents and the strength of selection pressures update at the end of each period.

## 3. Details

## 3.1 Implementation details

NetLogo v6.1.1

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